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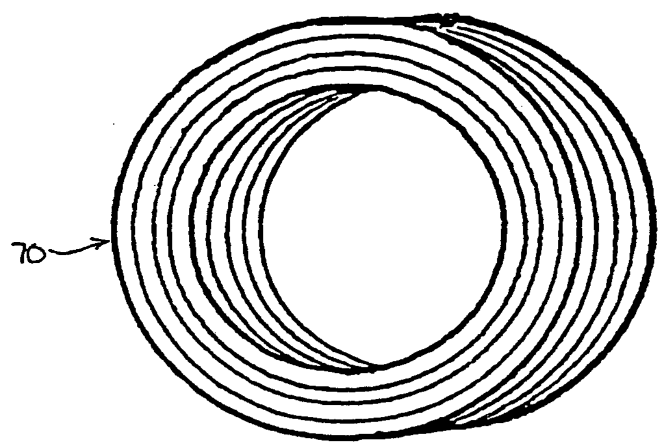

(57) Abstract

The invention is directed to an extremely low loss, low cost construction for magnetic flux return paths which may be utilized in electrical or electromechanical devices which include a changing magnetic fields. The magnetic flux is directed from one part of such a device to another through the magnetic flux return path, and have been susceptible to losses associated with eddy current flow and hysteresis. To minimize such losses, the magnetic flux return path is constructed of at least one layer formed from discrete magnetic material wire wrapped or otherwise formed in the desired return path configuration (26 in Figure 10). Forming the magnetic flux return path using layers of magnetic material wire provide ease of construction in certain applications and greatly reduce losses due to the smaller cross section of wire to eddy current flow and because of the minimization of skin effects associated with high frequencies and harmonics. The magnetic flux return path along with the method to form the flux return path are set forth.

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MAGNETIC FLUX RETURN PATH FOR AN ELECTRICAL DEVICE

BACKGROUND OF THE INVENTION

The invention is directed to electrical and electromechanical devices in which fluctuating magnetic fields are used to produce current flow, voltage, torque or other phenomena. More particularly, the invention is directed to a novel magnetic circuit which allows more efficient operation of electrical and electromechanical devices utilizing fluctuating magnetic fields which includes a magnetic flux return path with very low loss and an extremely flexible design.

In many electrical and electromechanical devices, fluctuating magnetic fields are utilized to produce current flow, voltage or torque to achieve desired output or work from the device. Such devices commonly include motors which utilize a rotor having permanent magnets producing a rotating magnetic field as the permanent magnets are rotated. Other examples of electromechanical devices include transformers which may contain a core of a high permeability magnetic material which acts to link one part of the transformer to another through electromagnetic fields generated within the core. Magnetic flux variation produced by means of an electromagnetic coil or primary winding energized by alternating current produces a varying magnetic flux within the magnetic circuit thereby inducing electric current proportional to the rate of variation of the magnetic flux in a secondary winding.

In both the motor and transformer devices, the fluctuating magnetic fields may lead to losses associated with eddy currents and hysteresis within the magnetic circuit. For example, in the case of a

transformer of normal construction, heat losses can develop with low frequency alternating current applications due to the resistance of the primary and secondary windings and eddy currents set up in the core of the transformer. Additionally, if the magnetic flux return path is such that magnetic saturation occurs, hysteresis losses may also be induced. In motors, where fluctuating magnetic fields are utilized to produce torque and power in an output shaft, the magnetic flux is directed from one magnetic pole to another found on a rotor through a fixed flux path. As the magnetic field within the return path varies due to rotation of motor parts, similar losses as with a transformer are induced.

Also, with electrical and electromechanical devices using high frequency alternating currents, both eddy current losses and hysteresis losses become greater due to the greater flux density within the magnetic material. Additionally, with high frequency applications, skin effects and magnetic saturation become of greater concern. Both eddy current and hysteresis losses generate heat which presents a major design problem for the electrical and electromechanical devices in which the magnetic circuit is used. To minimize hysteresis losses, previous applications have resorted to increasing the thickness of the flux return path to avoid magnetic saturation of the material.

Previous designs have also attempted to minimize eddy current losses by constructing the magnetic flux return of laminations or a number of thin iron plates which are insulated from one another. Special forms of transformer cores which are designed to minimize losses through linkage fields, are the spirally wound cores and toroidal cores. At low

frequencies, eddy current losses are a function of the thickness of the laminations making up the core and flux return path. Similarly, at high frequencies, both eddy current losses and hysteresis losses may be dependent upon the thickness of the laminations due to skin penetration effects. Thus, in the design of the magnetic circuit in these electrical and electromechanical devices, losses are generally minimized by providing a thick flux return path thereby avoiding saturation of the iron material normally used in their construction. The return path is made of a number thin laminates from a material having a high magnetic permeability wherein normally very thin laminates are desirable. Unfortunately, the degree of thinness obtainable for the laminations is limited by construction and fabrication associated problems as well as by cost.

As an example, a slotless brushless motor backiron using a plurality of laminations may be designed having a radial thickness of about 0.060 inches to accommodate a flux density which is limited to about 1.0T. The flux density can be limited to 1.0T when the rotor magnets have a flux density of about 0.4T which is a typical value for high flux ceramic magnets. A backiron construction having the desired thickness may be constructed of multiple laminations having conventional thicknesses of about 0.014 to 0.025 inches. Thinner laminations are possible but add to the cost of fabrication. For a typical DC motor with an output of 50 watts at 20,000 RPM the backiron parameters conventionally employed are a stack length of 1.5 inches and a diameter of 2 inches. To form a radial thickness of about 0.060 inches, the backiron weight will be approximately 0.167 pounds which must be

considered in the design of the motor. With a slotless brushless motor as described, the loss in the magnetic flux return path or backiron can be calculated as follows:

(2)

$$L_{BI} = afB_o^2 + b(tfB_o)^2$$

where L_{BI} is the loss in the backiron in watts/kg a and b are constants depending on the properties of the material, f equals the flux frequency in Hz., B_0 equals the flux density in the backiron in Tesla, and t equals lamination thickness in millimeters. In the equation for calculating the loss in the backiron as described above, the values of a and b will be known. For example, using an AISI grade M-15 iron laminate which is typically used for such laminations, these constants will have values of a = 0.019 and b = 6.2×10^{-4}. Flux saturation levels in most irons occurs at approximately 1.2 to 1.6 T and therefore saturation effects will not be considered in this example as the flux density has been limited to about 1.0 T. For a typical DC motor construction with the backiron as described above and an output of 50 watts at 20,000 RPM, the backiron stack length of 1.5 inches would require about 107 laminations which are about 0.014 inches in thickness or approximately 60 laminations if the thickness is about 0.025 inches. Cost considerations would require choosing between better performance characteristics for thinner laminations or less cost for the thicker laminations. The backiron loss, L_{BI}, for a construction using the lamination thickness of 0.025 inches with a radial length of about 0.060 inches for a 20,000 RPM, 2-pole pair motor calculates to a loss of about 13.7 watts which for a 50 watt output constitutes a 27.4% loss of

the output power. It should be recognized that the loss calculated above is for eddy current losses and has assumed that no magnetic saturation occurs resulting in other losses. The loss due to eddy currents is significant in itself and must be considered in the design of the motor.

Thus, in electrical and electromechanical devices which utilize varying magnetic fields, the magnetic flux return path would desirably be designed to carry any expected magnetic fields in the device with lower loss. The expected magnetic fields therefore dictate the requirements of the magnetic flux return path as to the material permeability and geometry necessary to channel a fluctuating magnetic field with low losses.

Other various electrical and electromechanical devices and examples of magnetic circuit design which attempt to limit losses are shown in U. S. Patent Nos. 4,459,653, 4,233,583, 4,065,705, 3,890,019 and 3,719,583.

SUMMARY OF THE INVENTION

Based upon the foregoing, there has been found a need to provide a magnetic circuit having a magnetic flux return path which allows further reduction of losses related to eddy currents or hysteresis in a very efficient and cost effective manner. There has also been found a need to provide a magnetic circuit having a magnetic flux path which greatly minimizes losses and provides ease of construction thereby enabling higher efficiency and lower manufacturing costs.

It is therefore a main object of the invention to provide a magnetic circuit usable with a variety of electrical and electromechanical devices which greatly

minimizes resistive losses as well as losses occurring due to eddy currents and hysteresis.

It is a further object of the invention to provide a magnetic circuit having a magnetic flux return path which greatly minimizes eddy current losses and hysteresis losses over a broad frequency spectrum and which is simple and cost effective to manufacture.

Another object of the invention is to provide a novel design for electrical and electromechanical devices utilizing fluctuating magnetic fields to produce current flow, voltage, torque or other desired effects and having a magnetic circuit with low losses internal to the magnetic material utilized for the circuit.

It is a further object of the invention to provide a magnetic circuit having a magnetic flux return path which can be designed to carry expected magnetic fields with less strict requirements on material permeability and geometry of the circuit and its construction.

It is yet another object of the invention to provide a method of producing a magnetic circuit element for a variety of electrical and electromechanical devices which provides very low eddy current losses and hysteresis losses over a broad frequency spectrum, and which is simple and cost effective to manufacture.

These and other objects of the invention are accomplished by a magnetic circuit which comprises a plurality of discrete windings of magnetic material wire wrapped or otherwise formed into layers to form the desired flux return path configuration. The layers of magnetic material wire substantially minimize losses due to eddy currents or hysteresis because of the

smaller cross section of wire to eddy currents and because of the minimization of skin effects associated with high frequencies and harmonics. The layers of magnetic material comprise high permeability material wire to form the low loss magnetic circuit. Eddy currents within the magnetic flux return path are then carried by the individual wires in the layers forming the flux return path. In this way, the cross section to eddy currents become the cross section of the wire, rather than a laminate edge as in conventional constructions, thereby reducing resistive losses and skin effects. The high magnetic permeability wire layers can be formed of smaller dimensional wire to further reduce eddy current losses and hysteresis losses over a broad frequency spectrum. The layers of magnetic material wire can be constructed of any wire geometry as for example square, flat, round, oval, triangular or other desirable cross sections to allow various packing characteristics in the layers for different applications. The magnetic material wire layers may be formed from a low cost material and provide great flexibility in fabrication and manufacturing for specific applications.

The method of producing the magnetic circuit of the invention for a broad span of devices, wherein the magnetic circuit provides very low eddy current losses and hysteresis losses over a broad frequency spectrum is also set forth. The method allows a variety of electrical and electromechanical devices to be designed for higher efficiency at a lower manufacturing cost. The magnetic circuit is constructed from a plurality of layers of a high permeability material wire which may be wrapped or wound in the general direction of the desired magnetic

flux flow. It is also found that individual layers in the magnetic circuit construction are tolerant to cross-layer and cross-winding fields enlarging the scope of use of the circuit.

BRIEF DESCRIPTION OF THE DRAWINGS

These and additional objects and advantages of the invention will become more apparent to those skilled in the art as the detailed description of the invention proceeds in conjunction with the drawings, wherein:

Fig. 1 is a side elevational view shown in section, of a DC brushless slotless motor having two pole pairs;

Fig. 2 is an end elevation shown in section of the motor of Fig. 1;

Fig. 3 is an enlarged sectional view of the magnetic flux return path of the invention for a fluctuating magnetic field;

Fig. 4 is a perspective view of a transformer using the magnetic flux return path of the invention to couple the primary and secondary windings of the transformer;

Fig. 5 is a perspective view of the magnetic flux return path as shown in Fig. 4;

Fig. 6 is a side elevational view of the magnetic flux return path as shown in Fig. 5;

Fig. 7 is a front elevation of the magnetic flux return path as shown in Fig. 5 demonstrating its construction for use with the transformer of Fig. 4;

Fig. 8 is a perspective view of a magnetic flux return path usable with an E-core transformer application;

Fig. 9 shows a torroidal magnetic flux return path for use in a torroidal transformer; and

Figs. 10a-10e show partial cross sections of various magnetic material wire usable in the magnetic flux return path.

DETAILED DESCRIPTION OF THE INVENTION

Turning now to Figs. 1 and 2, a generalized DC slotless, brushless motor 10 is shown. The motor 10 includes a cylindrically symmetric rotor 12 comprising an output shaft 14 having a soft iron fixed flux path 16 and two pole pairs of permanent magnets 18 situated on the rotor 12. The rotor 12 is supported for rotational movement about the output shaft 14 inside a concentrically wound field stator 20 by means of bearing supports 22 supporting the output shaft 14 of the motor 10. A direct current is introduced into the field winding 24 of the stator 20 to cause the rotational movement of the rotor 12 and the permanent magnet pole pairs 18 thereof. The soft iron fixed flux path 16 provides a low reluctance path for the magnetic field generated by the permanent magnet pole pairs whose polarity is indicated in Fig. 2. The magnets 18 may be of conventional design and are typically constructed of samarium cobalt, barium or strontium ferrite, neodymium iron magnets or the like. The magnetic circuit, indicated at 30 in Fig. 2 is completed by the addition of the magnetic flux return path 26 embodying the principles of the present invention.

The magnetic flux return path 26 for the rotating magnetic field produced by the permanent magnets 18 of the rotor 12 is formed by making a multilayer winding assembly of discrete high

permeability material wire. The magnetic flux return path 26 for the rotating magnetic field produced by the rotor permanent magnets 18 provides very low eddy current losses and hysteresis losses over a broad frequency spectrum of operation. The low loss magnetic flux return path forming part of the magnetic circuit of the motor 10 achieves very low eddy current losses and hysteresis losses by forming the flux path over a plurality of high permeability magnetic wires which are wrapped into layers so as to extend the length of the produced magnetic field. The flux return path 26 also has a thickness such that the material does not become magnetically saturated leading to hysteresis losses.

Additionally, as compared to the conventional use of thin laminations of iron wherein the cross section to eddy currents become the cross section of the laminate edge, the magnetic flux return path 26 of the present invention reduces eddy current losses by forming the cross section to eddy currents as the cross section of the magnetic material wire thereby reducing resistive losses commonly found at the laminate edges in a conventional construction. As seen in Fig. 3, eddy currents 32 are formed in each individual magnetic flux return path element or wire 34 which make up flux return path 26. This effect can be facilitated by forming the high permeability magnetic material wires of smaller dimensional cross section to further reduce eddy current and hysteresis losses over a broad frequency regime.

As seen in Fig. 1, the magnetic flux return path 26 of the present invention is constructed by the use of thin flat high permeability material wire which is wrapped in a multilayer, close turn coil form over the extent of the magnetic field produced by the

permanent magnets 18 situated on the output shaft 14. The expected magnetic fields produced by the permanent magnets 18 determine the thickness of the multilayer, close turn magnetic flux return path 26 to prevent saturation in the flux return path. As seen in Fig. 2, the magnetic circuit 30 shows that magnetic flux from the north pole magnet is directed through the field winding 24 and into the wound magnetic flux return path 26. Once in the magnetic flux return path 26, the flux is distributed in a generally circumferential path in the multiple layered backiron construction and then returns to the south pole magnet of the rotor 12. The magnetic circuit is completed with the solid soft iron member 16 and subsequently back into the north pole magnet as shown.

The magnetic flux produced by the rotating rotor 12 thus forms a loop from north pole into the wound return path and back into the south pole following the direction of the high permeability path formed by the return path of the invention. The individual layers of high permeability wire may be wrapped or wound in the general direction of the desired flux, but it should be recognized that individual layers may be crossing the flow of flux in some areas. The magnetic flux return path 26 will not significantly disturb the flux distribution or flux magnitude at the regions of such crossings as long as the length of the crossing path is minimized. The individual layers of wound wire are tolerant to cross-layer and cross-winding fields as long as the crossing length is short and the packing fraction of the wire layers is high. It should be evident that a "solenoid" construction is possible for a motor backiron construction wherein the produced magnetic field will

cross strands of wire along some segment of the solenoid construction, but in general will follow the direction of the wound flux return path.

In the motor 10, the magnetic circuit 30 as seen in Fig. 2 interacts with an opposing magnetic field produced by current flowing in the field winding 24 thereby producing a reaction torque which causes the shaft 14 to which the magnets 18 are coupled, to rotate. The soft iron core 16 to which the magnets 18 are attached experiences only a fixed magnetic flux in the motor 10 and therefore if element 16 is not magnetically saturated, there will be no motor performance loss due to hysteresis or eddy currents. It should be recognized however, that as the shaft 14 rotates, a given sector of the magnetic flux return path 26 will experience a magnetic field increase to a high value and then a decrease to zero each time a magnetic pole pair rotates pass a given position. This increase then decrease in magnetic flux causes an electrical current to be generated in the magnetic flux return path material which has conventionally caused a power loss exhibited as heat loss. In addition, the reversing magnetic field may also produce hysteresis losses.

The wound cross section of high permeability magnetic material wire forming the magnetic flux return path 26 can significantly reduce heat losses especially in high field strength and high frequency applications. The efficiency of the magnetic circuit will depend upon the size of magnetic material wire chosen and the frequency of operation which may be defined as the rotational speed times the number of pole pairs in the motor. Both hysteresis and eddy current losses are proportional to the square of the flux density. Also,

hysteresis losses are proportional to the frequency of operation and eddy current losses to the square of the frequency. The magnetic circuit return path 26 thus will reduce eddy current and hysteresis losses by better accommodating the flux generated in the circuit especially at higher field strengths and higher frequencies.

Losses may also occur due to skin effects especially at higher frequencies which occur where lines of flux are squeezed to the outer perimeter of the flux bearing structure. As flux density in the perimeter increases towards saturation, heat losses may also increase. As long as the thickness of the magnetic flux return path 26 is chosen to accommodate the expected magnetic fields and prevent saturation, skin effects can be minimized. Also, the use of smaller cross sectional wire as opposed to laminates or larger diameter wire can minimize the potential for skin effects.

Thus, in the design of the magnetic flux return path 26, the backiron is close wound with a high permeability wire into multiple layers as shown. The number of layers is chosen to provide a flux path of sufficient depth to prevent saturation in the return path 26. Similarly, the wire cross section dimensions are determined by the acceptable eddy current and hysteresis losses in the particular application for the motor 10. As shown in Fig. 1, the high permeability wire used is a thin, flat wire which is susceptible to standard coil winding techniques to enable forming of the magnetic flux return path 26 at a very low cost. Additionally, due to the greater effectiveness of the flux return path, very low cost materials such as very low carbon iron rather than high silicone or high

nickel iron can be used. It should be evident that the magnetic flux return path 26 can be manufactured easily and effectively at a very low cost while operating more efficiently than with use of thin laminations or the like. It is important that the packing fraction of the individual wires in the layers forming the magnetic flux return path 26 be high to avoid skin effects and facilitate efficient flux distribution in the path. Standard coil winding techniques can achieve a very high packing fraction such that manufacturing can be accomplished cost effectively. Similarly, changes in size or shape requirements can also be made with little or no cost in procedures or tooling for their production.

As an example, a backiron construction formed utilizing the magnetic circuit of the present invention including a magnetic flux return path constructed of close wound magnetic material wire may be designed as follows. For a typical brushless, slotless DC motor with an output of 50 watts at 20,000 RPM, the backiron parameters may comprise a stack length should be about 1.5 inches having a diameter of about 2 inches. The backiron radial thickness would be about 0.060 inches to limit the flux density to about 1.0T when the rotor magnets have a flux density of 0.4T. For a wire wound backiron construction in accordance with the invention, a flat ribbon wire may be used which has dimensions of about 0.06 inches width and 0.005 inches in thickness. To accommodate the expected magnetic fields, 25 turns of flat ribbon wire per layer and 12 layers will give a backiron construction having the desired parameters. The wire wound backiron construction can be fabricated using a standard coil winding machine. For a 20,000 RPM, 2-pole pair motor having a 50 watt output, the

loss associated with a backiron construction in accordance with the present invention will be about 1.88 watts or about 3.7% of the total output power. As compared with a typical motor construction using thin laminations in the construction of the backiron, an extremely significant improvement in the efficiency of the motor and the magnetic circuit thereof is achieved with a lower cost construction.

As a design consideration, the cross section of the wires making up the wound magnetic return path can be chosen for each particular application so as to operate as effectively and efficiently as possible. The skin penetration depth of the magnetic field will depend upon the particular cross section of the high permeability wire. The skin penetration depth can be found for a round wire and extrapolations can be made to other cross-sectional shapes in the design of the magnetic flux return path 26.

The application of the wound magnetic flux return path of the present invention is quite general and is not limited to a motor application as shown in Figs. 1 and 2, but may be used in other applications. The low cost materials and fabrication techniques make the use of a wound magnetic flux return path both easy and cost effective. The wound magnetic flux return path using magnetic material wire having small cross sectional area which is wound to provide high packing fraction is especially useful in high frequency applications wherein its low cost and superior performance are extremely beneficial. The reduction of eddy current and hysteresis losses is especially apparent at high frequencies where skin effects are also minimized.

As shown in Figs. 4-7, another application in which the magnetic flux return path of the invention may be utilized is with a transformer 50. The transformer 50 comprises a primary winding 52 as well as a secondary winding 54 used for stepping up alternating current to high voltages or stepping down the voltage at the point of consumption. A magnetic flux variation is produced by means of the primary winding 52 energized by alternating current such that an induced electric current can be obtained from the secondary winding 54 of the transformer 50. The primary winding 52 and secondary winding 54 are mounted on a core 56 which acts as the magnetic flux return path completing the magnetic circuit in the transformer. In the construction of the transformer 50, a solid square coil may be first wound of a thickness to contain the magnetic field expected from the primary winding 52 and with wire dimensions chosen to avoid skin effects. This solid square coil forming the magnetic flux return path is shown in Fig. 5 and may be formed by standard coil winding techniques similarly to the motor backiron. The wire thickness diameter is determined by the frequency of the input and the coil cross sectional area is determined by the flux density such that the layers of magnetic material contain sufficient volume to prevent saturation. The solid square coil 56 can be held together using non-conductive clamping bands (not shown) placed under the electric coils, while conductive clamping bands 58 can be placed outside the electric coils to prevent losses in the clamping bands. The winding is then cut as shown at 60 in Figs. 6 and 7, and the primary and secondary coils may then be wound on the assembly or simply clipped to the assembly as desired. After

application of the primary and secondary windings 52 and 54 respectively, the solid square coil 56 may then be secured together along its cut portions to form the low loss transformer as shown in Fig. 4. It should be evident that other means of preventing the wrapped solid square coil from unwinding may be utilized other than the clamps 58 shown. For example, encapsulating the formed coils or forming the coil with self bonding wire may accomplish the same effect.

Turning now to Fig. 8, and E-core transformer application is shown. The E-core 60 comprises a pair of solid square coils similar to that shown in Fig. 4 which may be manufactured similarly to the transformer described with reference to Figs. 4-7. The core 60 will form a double closed magnetic circuit and may present a more efficient design for the transformer. The E-core application may be provided with primary and secondary windings wrapped in concentric form with the primary winding being within the secondary at location 66 around a portion of each solid square coil 62 and 64 respectively.

Similarly, a toroidal core 70 as seen in Fig. 9 may comprise a multilayer wound thickness of high permeability magnetic material wire. Primary and secondary windings may be wrapped on opposite sides of the toroid 70 to function as a transformer. It should be recognized that the applications as described with reference to 1-9 are specific examples where the magnetic flux return path of the present invention are particularly applicable, but other applications wherein a magnetic circuit is utilized with a magnetic flux return path may be suited to the construction of the present invention. The layers of high permeability magnetic wire provide ease of construction and

substantially minimize losses due to eddy currents or hysteresis because of the smaller cross section of wire to eddy currents and because of the minimization of skin effects associated with high frequencies and harmonics. It should be evident that the magnetic flux return path can be formed in any desired configuration for the particular application while not incurring any substantial increase in manufacturing cost or procedures with such variations. The present invention provides a method of producing a magnetic circuit element for a broad span of devices which provides very low eddy current losses and hysteresis losses especially at high frequencies. The individual wires and layers of the magnetic flux return path may be wrapped or wound in the general direction of the desired flux flow but individual layers are also tolerant to cross-layer and cross-winding fields. Similarly, small gaps will not alter the overall efficiency of the return path so long as the crossing length is short and packing fraction of the wire layers is high.

The low loss characteristics associated with a magnetic flux return path constructed in accordance with the present invention can be seen from the following example. For a toroidal core design using laminations as is conventional in the prior art, at an operating frequency of about 20,000 Hz., the design may be as follows. The core diameter may be about one inch with a core cross section of about 0.1 inches by 0.1 inches. For laminations having a thickness of 0.010 inches being a typical thickness, the above core cross-section would produce a core weight of about 0.0094 pounds or 0.0043 kg. If B_0 or the flux density in the core is limited to 1.2T, the flux return path losses

may be calculated in accordance with Equation 1, and will be about 101 watts.

A similar toroidal core design using a magnetic flux return path constructed in accordance with the present invention may use a flat ribbon wire having a thickness of about 0.001 inches and a width of about 0.025 inches. The toroidal core may be constructed of 100 layers of four turns each wound on a standard coil winding apparatus to form a core diameter of one inch with a core cross section of 0.1 inches by 0.1 inches. At the operating frequency of 20,000 Hz. and a flux density, B_0, which is limited to 1.2T, flux return path losses for the toroidal core constructed in accordance with the present invention will be about four watts, which as compared with conventional core constructions shows the significant reduction of losses so as to provide an efficient, simple and cost effective magnetic flux return path construction.

As seen in Figs. 10a - 10e, the windings or layers of high permeability magnetic material wire can be constructed of any wire geometry such as, but not limited to, square cross section as seen in Fig. 10a, round as seen in Fig. 10b, triangular and seen in Fig. 10c, oval as seen in Fig. 10d or flat or ribboned as seen in Fig. 10e. It should be recognized that the various cross sections of wire as seen in Figs. 10a-10e allow greater packing fraction to be achieved based on the cross section with standard coil winding techniques or the like. It should also be recognized that combinations of various cross sections may be used as desired. In some applications, an oxide coating on a bare wire may be adequate to provide contact resistance to eddy current circulation or a thin non-conductive coating on the wire may be used. The particular cross-

section or combination utilized must only take into account the desired core permeability, which is dependent upon the packing factor and the material permeability itself. Thus, the particular packing fraction achievable with any particular cross section or winding technique must be taken into consideration when determining the overall volume to saturation of the magnetic flux return path.

The present invention has thus been shown to provide an efficient and cost effective magnetic flux return path assembly which provides great flexibility in the design and fabrication thereof. The wire wound magnetic flux return path may be used in lieu of laminations and will reduce the eddy current and hysteresis losses as well as minimize skin effects while reducing power consumption in the application. By utilizing discrete wires wound in a tight wrapped form to generate the magnetic flux return path. The number of windings and layers of wires can be easily chosen to accommodate the proper flux density to avoid magnetic saturation in the device. The dimensions of wire can be chosen based upon the flux density and frequency of the application and does not require directional characteristics due to flow effects as this magnetic flux return path relies upon field effects. Although various specific embodiments using the magnetic flux return path of the invention have been set forth, it should be recognized that the flux return path may be utilized in other applications and various modifications and variations are possible and contemplated within the scope of the appended claims.

WHAT IS CLAIMED IS:

1. A low loss magnetic flux return path comprising,

a plurality of discrete windings of magnetic material wire positioned in closely adjacent relationship to form at least one layer of magnetic material extending approximately the length of a generated magnetic field,

the thickness of said at least one layer of said windings being designed to substantially accommodate said magnetic field to avoid magnetic saturation,

wherein said windings will provide a high magnetic permeability path for said magnetic field to distribute generated magnetic flux with very low eddy current or hysteresis losses.

2. A low loss magnetic flux return path as in claim 1, wherein,

said magnetic material wire is a very small dimensional cross section allowing said plurality of windings to be formed in a very close packed configuration.

3. A low loss magnetic flux return path as in claim 1, wherein,

eddy currents generated and circulating within said magnetic flux return path are carried by each of said discrete windings of magnetic material wire to minimize losses due to eddy currents.

4. A low loss magnetic flux return path as in claim 3, wherein,

the cross section to eddy currents within said magnetic flux return path is the cross section of said magnetic material wire.

5. A low loss magnetic flux return path as in claim 1, wherein,

said plurality of discrete windings are wound in the general direction of the desired flow of said magnetic flux.

6. A low loss magnetic flux return path as in claim 1, wherein,

said magnetic material wire is formed of a high magnetic permeability material.

7. A low loss magnetic flux return path as in claim 1, wherein,

said return path is constructed of a plurality of layers formed from said plurality of windings in a closely packed configuration and the cross section of said magnetic material wire is adapted to minimize skin effects and to facilitate efficient flux distribution in said return path.

8. A low loss magnetic flux return path as in claim 1, wherein,

said magnetic material wire has a cross sectional geometry which allows a high packing fraction to be obtained in said at least one layer of said discrete windings.

9. A low loss magnetic flux return path as in claim 1, wherein,

said return path is used in an electrical or electromechanical device utilizing a fluctuating magnetic field to distribute flux generated with minimized eddy current or hysteresis losses.

10. A magnetic circuit having a low loss magnetic flux return path comprising,

a source of varying magnetic field to generate magnetic flux,

a magnetic flux return path positioned in said varying magnetic field to channel said magnetic flux induced therein by said magnetic field,

said magnetic flux return path being formed of a plurality of discrete windings of an magnetic material wire positioned in closely adjacent relationship to form at least one layer of magnetic material extending approximately the length of said magnetic field and having a thickness to substantially accommodate said magnetic field and avoid magnetic saturation.

11. A magnetic circuit as in claim 10, wherein,

said source of varying magnetic field comprises at least one permanent magnet being rotated, wherein said magnetic flux return path is positioned circumferentially about said rotating permanent magnet.

12. A magnetic circuit as in claim 10, wherein,

said source of varying magnetic field is an electrical field winding wherein said magnetic flux return path is magnetically linked to said winding.

13. low loss magnetic flux return path as in claim 10, wherein,

said magnetic material wire is of very small dimensional cross section allowing said plurality of windings to be formed in a very close packed configuration.

14. A low loss magnetic flux return path as in claim 10, wherein,

eddy currents generated and circulating within said magnetic flux return path are carried by each of said discrete windings of magnetic material wire to minimize losses due to eddy currents.

15. A low loss magnetic flux return path as in claim 14, wherein,

the cross section to eddy current circulation within said magnetic flux return path is the cross section of said magnetic material wire.

16. A low loss magnetic flux return path as in claim 10, wherein,

said plurality of discrete windings are wound in the general direction of the desired flow of said magnetic flux.

17. A low loss magnetic flux return path as in claim 10, wherein,

said magnetic material wire is formed of a high magnetic permeability material.

18. A low loss magnetic flux return path as in claim 10, wherein,

said return path is constructed of a plurality of layers formed from said plurality of windings in a closely packed configuration and the cross section of said magnetic material wire is adapted to minimize skin effects and to facilitate efficient flux distribution in said return path.

19. A method of forming a low loss magnetic flux return path comprising the steps of,

providing a forming means having a predetermined shape for constructing said return path,

positioning a plurality of discrete magnetic material wire windings on said forming means to obtain the desired configuration for said return path,

said step of positioning being continued to form a plurality of closely adjacent discrete windings into at least one layer extending approximately the length of an expected magnetic field having a thickness to substantially accommodate said magnetic field.

20. A method of forming a low loss magnetic flux return path as in claim 19, wherein,

said winding of said magnetic material wire is conducted by coil winding techniques to achieve a very high packing fraction and allow desired shapes to be obtained and varied easily.

FIG. 1

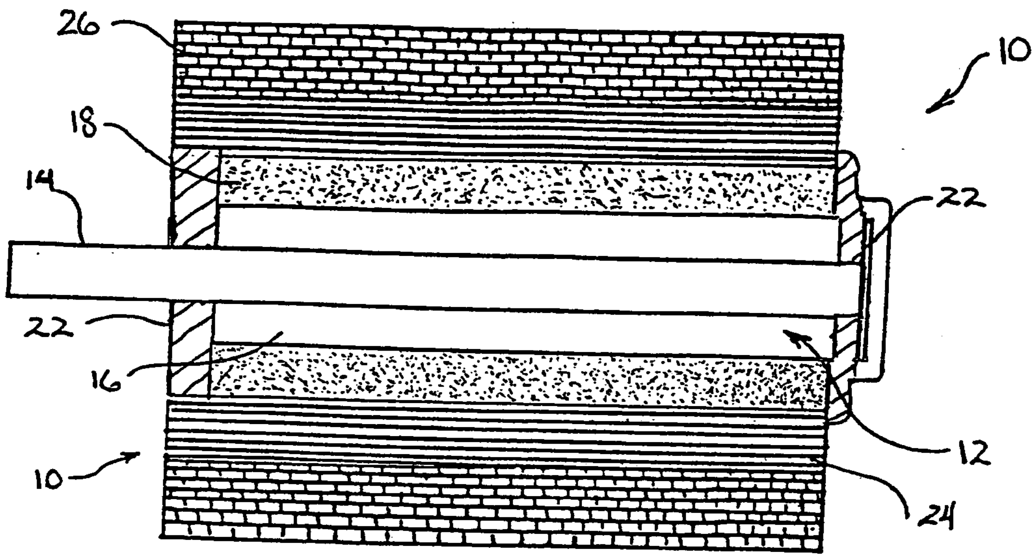


FIG. 2

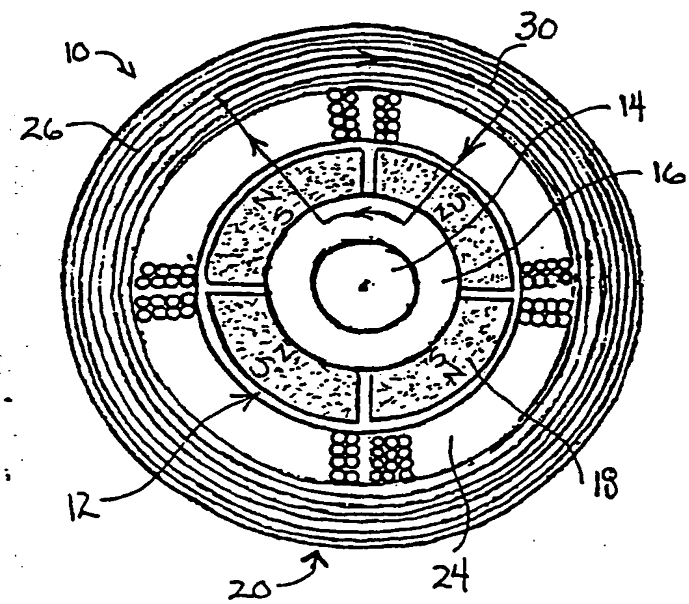


FIG. 3

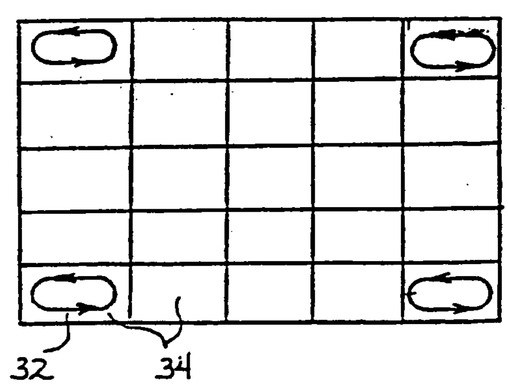


FIG. 4

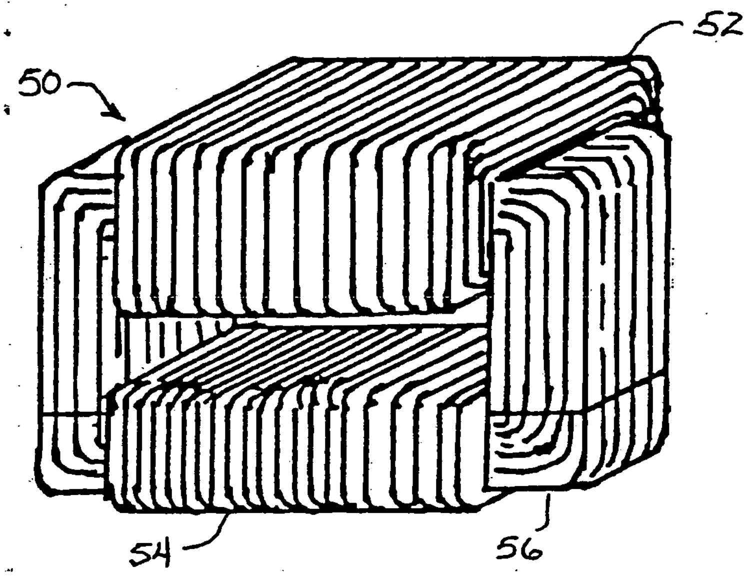


FIG. 5

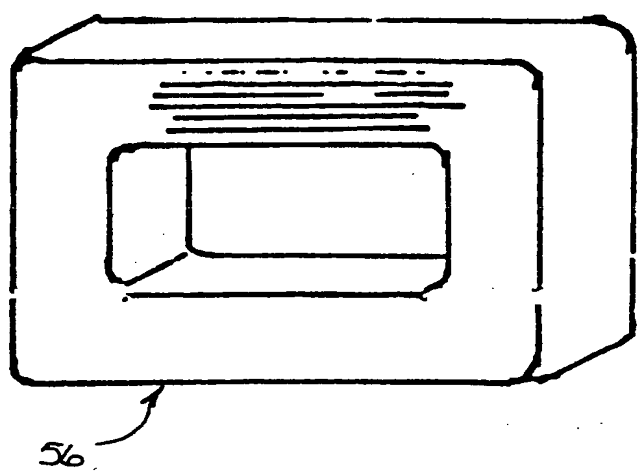


FIG. 6

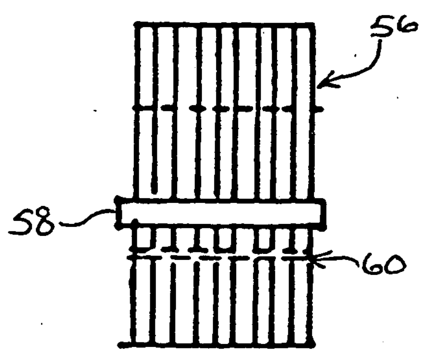


FIG. 7

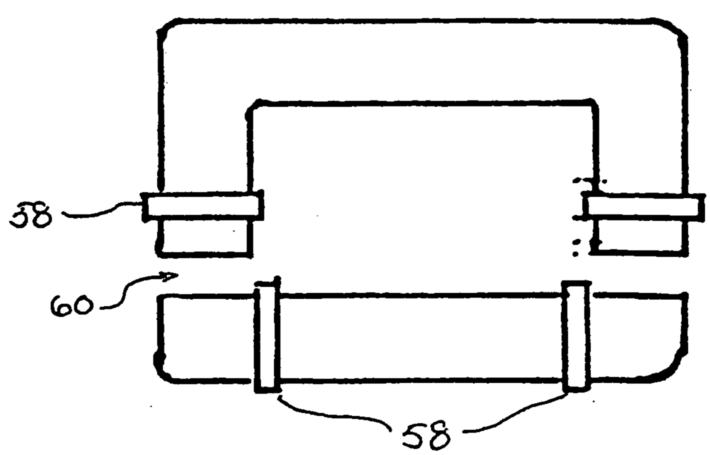


FIG. 8

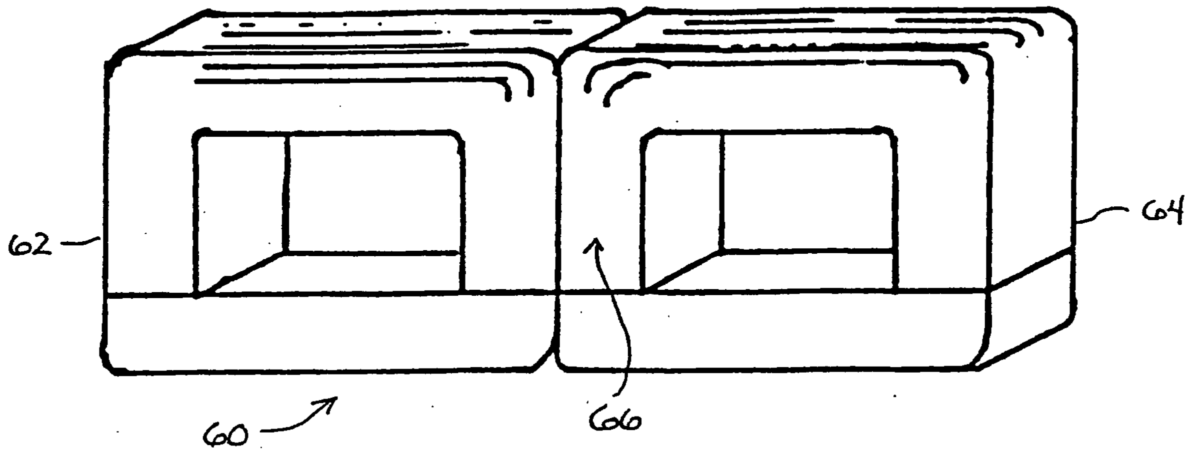


FIG. 9

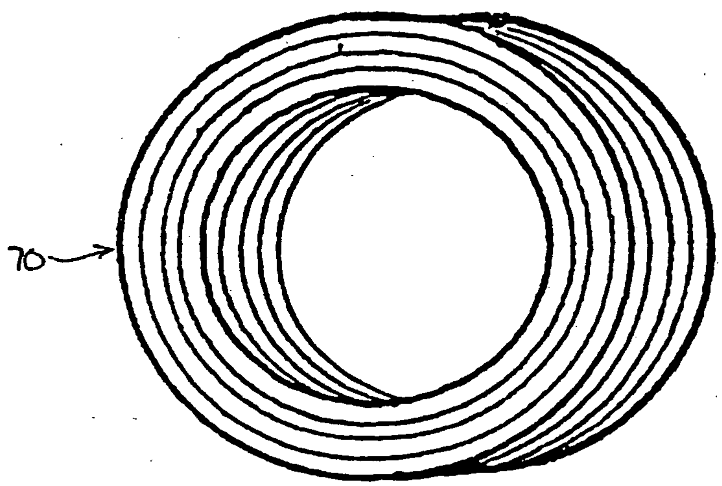


FIG. 10A

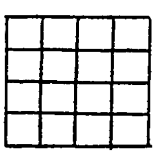


FIG. 10B

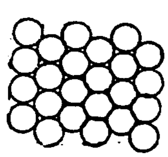


FIG. 10C

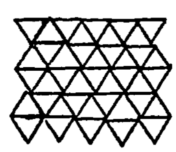


FIG. 10D

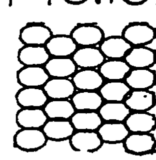
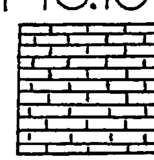


FIG. 10E



INTERNATIONAL SEARCH REPORT

International Application No PCT/US07585

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [3]

According to International Patent Classification (IPC) or to both National Classification and IPC
IPC(5): HO2K 1/12; HO1F 17/00; HO1F 3/00
US CL.: 310/254,259; 336/177; 335/297

II. FIELDS SEARCHED

Minimum Documentation Searched [4]

Classification System	Classification Symbols
US	310/254,259; 336/177; 335/297

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [5]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [14]

Category *	Citation of Document, [16] with indication, where appropriate, of the relevant passages [17]	Relevant to Claim No. [18]
X	US, A, 3,983,435 (SIMS) 28 September 1976 See column 3, lines 36-40 and column 4, lines 57-60.	1-11,13-20
X	US, A, 847,008 (KITSEE) 12 March 1909 See entire document.	1-10,12-20

* Special categories of cited documents: [15]

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search [2]	Date of Mailing of this International Search Report [2]
05 FEBRUARY 1991	11 MAR 1991
International Searching Authority [1]	**Signature of Authorized Officer**
ISA/US	NGUYEN NGOC-HO INTERNATIONAL DIVISION RAYMOND M. BARRERA Ngoc-Ho Nguyen

Form PCT/ISA/210 (second sheet) (May 1986)